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(54) Abstract Title
Method of forming a circuit element by droplet deposition

(57) A circuit element (e.g. resistor, capacitor, inductor) is formed by a drop-on-demand deposition technique by ejection of multiple droplets 20 (Fig.1) of a deposition material from deposition heads 22A-C (Fig.1) onto a surface. The deposition heads are directed towards a single drop site 24 (Fig.1), or they can be directed towards respective drop sites (Fig.2). A resistor 200 (Fig.4) formed by the technique comprises multiple discrete portions 204,206 (Fig.4), at least two adjoining portions being formed from different deposition materials. Once deposited, the resistor may be subjected to radiation treatment by a UV light system (50,Fig.3) if required. In addition, a method of imparting electrical conduction to part of a partially cured insulating layer using electrostatically focused electrically conductive particles is disclosed.

Fig. 1

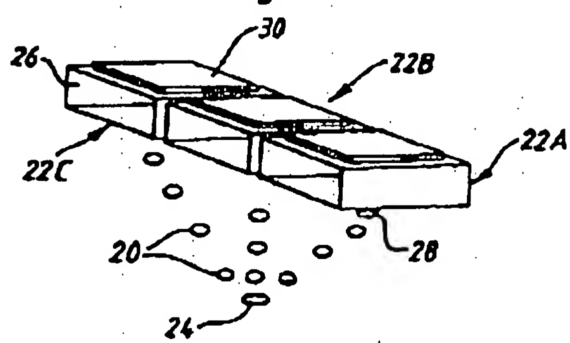
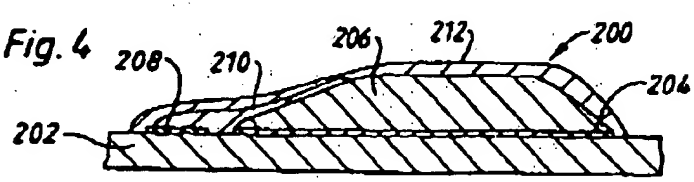


Fig. 4



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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

Fig. 1

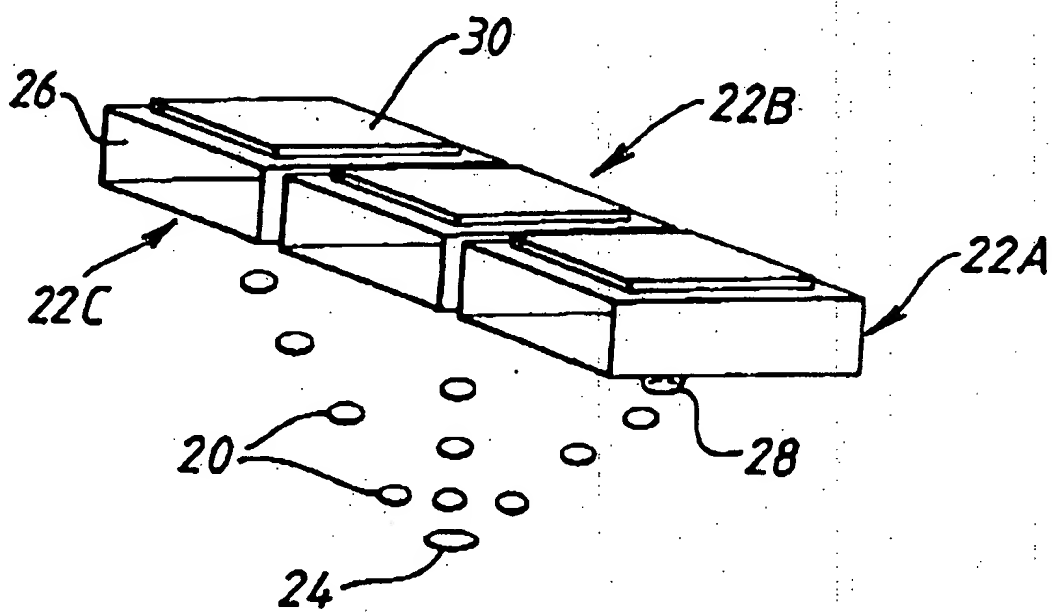
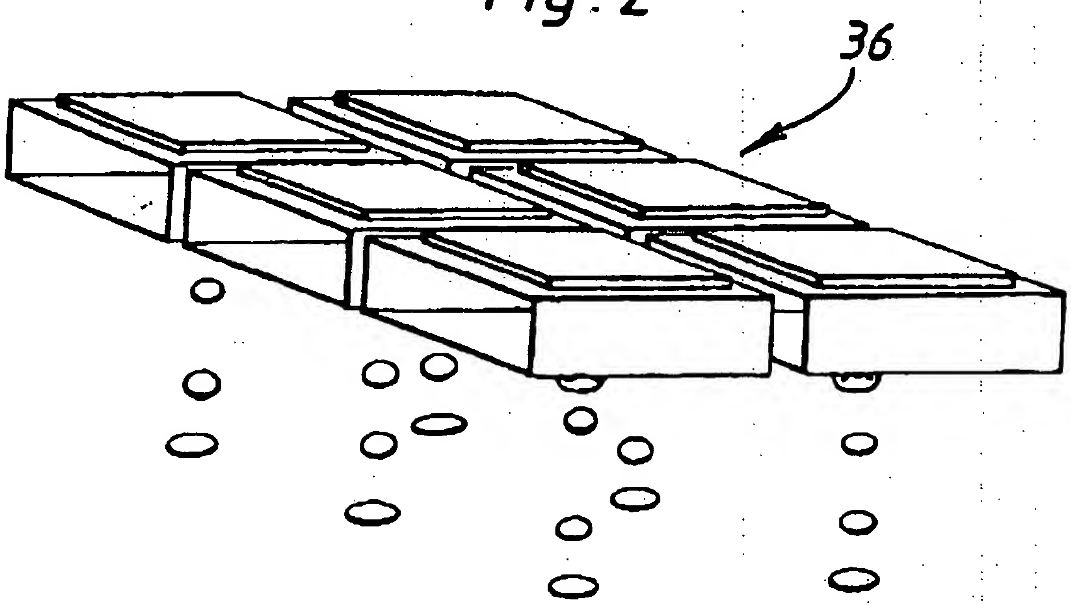


Fig. 2



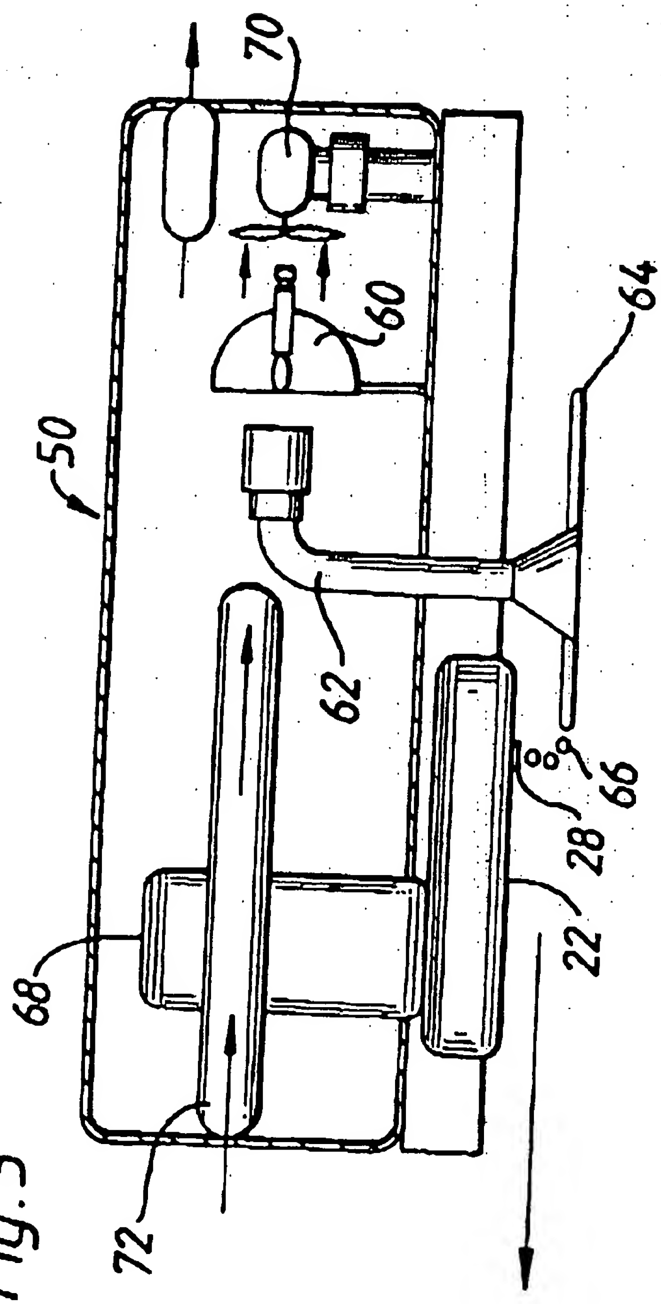


Fig. 3

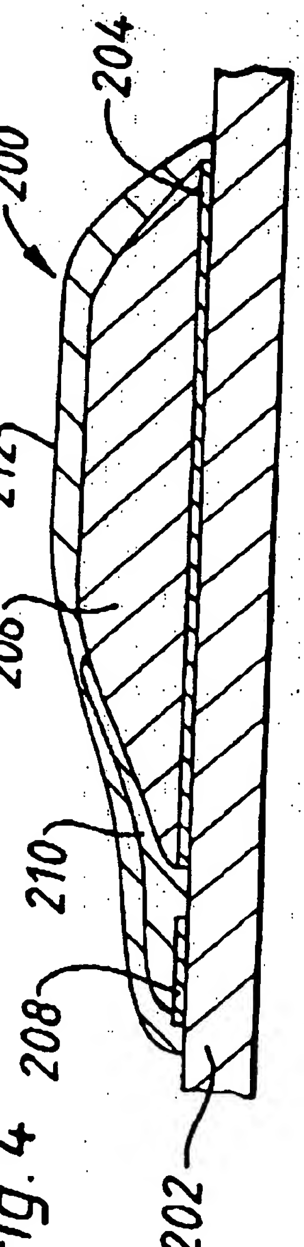


Fig. 4

Fig. 5

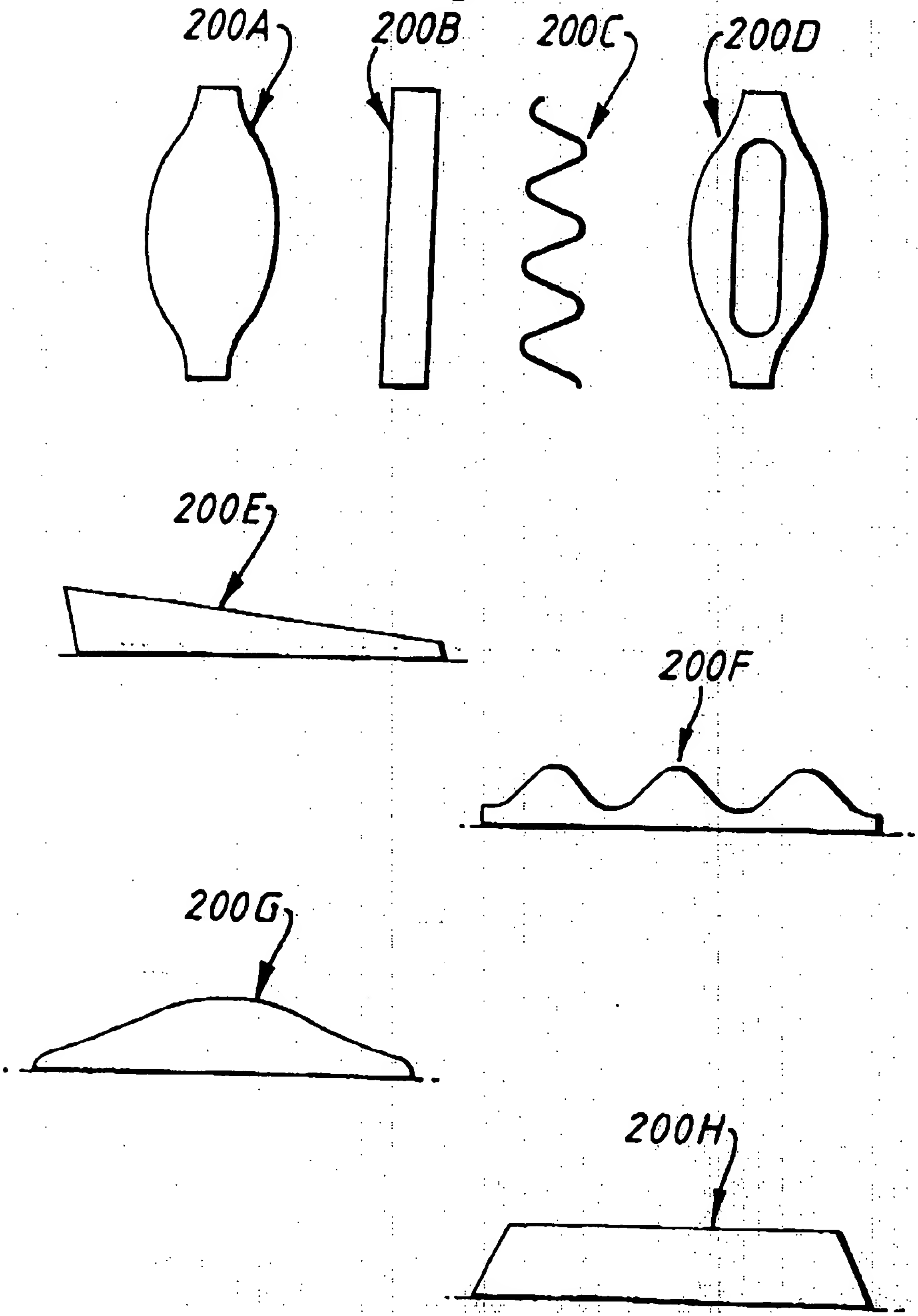


Fig. 6

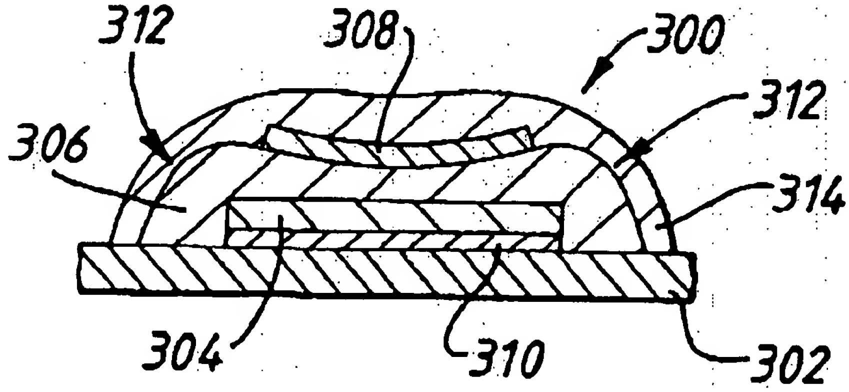


Fig. 7(a)

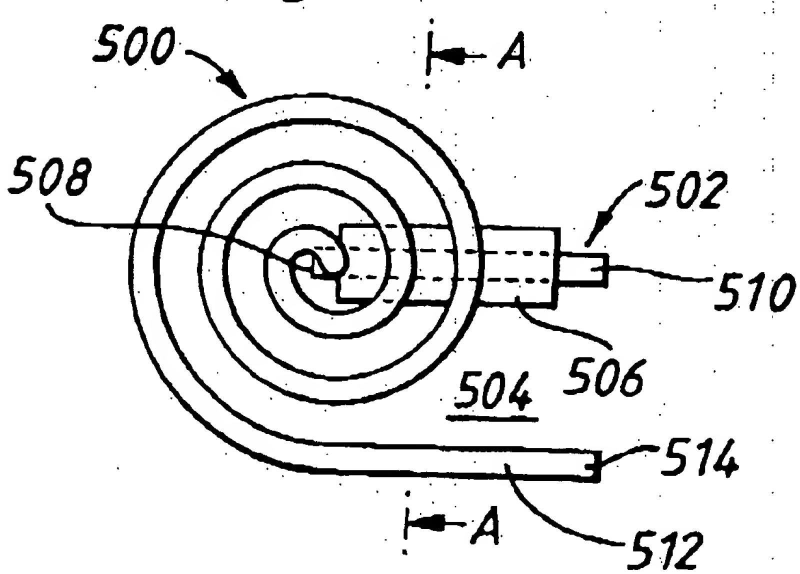
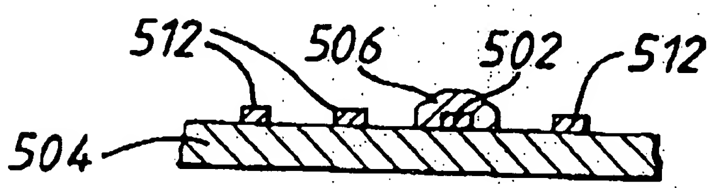


Fig. 7(b)



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METHOD OF FORMING A CIRCUIT ELEMENT ON A SURFACE

The present invention relates to a method for forming a circuit element on a surface.

In one aspect, the present invention addresses the problem of accurate and fast formation of a circuit element on a surface.

Drop-on-demand printing is a known printing technique whereby a droplet of ink is ejected from a inkjet printer head. The droplet impacts with a porous or semi-porous surface, dries and forms a spot which forms a recognisable pattern and colour such as type.

According to one aspect of the present invention there is provided a method of forming a circuit element on a surface using the technique of droplet ejection to deposit droplets of deposition material, said method comprising depositing a plurality of droplets on said surface to form said element so as to comprise multiple discrete portions, at least two adjoining portions being formed from different deposition materials.

The term "circuit element" used herein connotes any component of an electric circuit which comprises at least one of insulating, dielectric and conducting material, including conductive tracks between components.

In another aspect, the present invention provides a circuit element formed on a surface using the technique of droplet ejection to deposit droplets of deposition material, said element comprising multiple discrete portions, at least two adjoining portions being formed from different deposition materials.

The present invention can make use of an ink-jet printhead to eject droplets of fluid that coalesce on a surface and when suitably dried form a three-dimensional feature. By using the technique of droplet ejection, a circuit

element can be formed using a relatively fast process that requires no hard photolithographic masks for patterning. The process can be relatively efficient, in that material is deposited only where it is required in the finished product, that is, there is no need to use any process for the removal of deposited material.

The volume of each droplet is typically between 1 picolitre and 1 microlitre. This enables the final shape of the circuit elements to be accuratley controlled during the formation thereof, and enables a wide variety of different shapes of circuit elements to be formed.

The application of the invention is wide. For instance, flexible printed circuits can be fabricated using conductive print to provide contact to the selected element for electrical access and to provide a conductive route between circuit elements.

The circuit element may comprise an electrically conductive element.

The conductive element may be formed from polyaniline material comprising a suitable electron injecting barrier material, such as TCNQ.

The circuit element may comprise a plurality of stacked electrically conductive elements connected by via holes to provide electrical conduction between layers.

The circuit element may further comprise at least one isolation layer, the or each isolation layer being disposed between adjacent elements. The isolation layer prevents electric field interactions/interference between adjacent powered electrodes.

In a third aspect, the present invention provides a method of forming an electronic circuit element comprising stacked electrically conductive elements

on a surface using the technique of droplet ejection to deposit droplets of deposition material, said method comprising depositing a plurality of droplets to form a first conductive element, depositing a plurality of droplets to form an isolation layer on said first conductive element and depositing a plurality of droplets on said isolation layer to form a second conductive element.

The droplets forming the conductive elements and the droplets forming the isolation layer may be supplied by respective droplet deposition printheads.

Alternatively, the droplets forming the conductive elements and the droplets forming the or each isolation layer may be supplied by a butted droplet deposition printhead having a plurality of separate fluid supplies.

The or each electrically conductive element may comprise a track on a printed circuit board.

The conductivity of the or each electrically conducting element may be in the range from 10^2 to 4×10^5S.cm^{-1}.

In a preferred embodiment, the circuit element is an electrical resistor.

The resistor may be formed from polymeric material and include a layer for promoting adhesion between the polymeric material and the surface, said method comprising the steps of depositing said layer on said surface and depositing said polymeric material on said layer to form said resistor.

The polymeric material may comprise one of PTFE, PMMA and polyaniline containing a suitable electron injecting barrier material.

The droplets forming the polymeric material and the droplets forming the adhesion promoting layer may be supplied by respective droplet deposition printheads.

The droplets forming the polymeric material and the droplets forming the adhesion promoting layer may be supplied by a butted droplet deposition printhead having a plurality of separate fluid supplies.

The method may further comprise the step of subjecting the resistor to infra-red radiation to "reflow" the resistor in order to maximise the "void fraction" of the resistor. This can influence the resistance value of the resistor.

In another preferred embodiment, the circuit element is an electrical capacitor.

Preferably, the capacitor comprises a first polymeric conductive layer formed on said surface, a polymeric dielectric layer formed on said first conductive layer and a second polymeric conductive layer formed on said dielectric layer, said method comprising the steps of depositing said first polymeric conductive layer on said surface, depositing said polymeric dielectric layer on said first conductive layer and depositing said second polymeric conductive layer on said dielectric layer.

The capacitor may further comprise a layer for promoting adhesion between said first conductive layer and said substrate, said method comprising depositing said layer on said substrate before deposition of said first conductive layer.

Opposing side edges of said dielectric layer may be locally thickened to eliminate electric field breakdown due to current bunching at the edges of the conductive layers.

The dielectric layer may be fromed from one of siloxane and fluorinated polyimide.

The droplets forming respective layers may be supplied by respective droplet deposition printheads.

Alternatively, the droplets forming respective layers are supplied by a butted droplet deposition printhead having a plurality of separate fluid supplies.

In another preferred embodiment, the circuit element is an electrical inductor.

The method may further comprise the step of isolating hermetically said circuit element by depositing an isolating layer on the surface thereof. The isolating layer may be formed from an ormocer.

In another aspect, the present invention provides a method of forming a plurality of circuit elements on a surface using the technique of droplet ejection to deposit droplets of deposition material, said method comprising depositing a plurality of droplets to form a first circuit element, depositing a plurality of droplets to form an isolation layer on said first circuit element and depositing a plurality of droplets on said isolation layer to form a second circuit element.

This enables, for example, complete LCR circuits to be formed using the technique of droplet deposition.

An important consequence of the ability to print multiple-level conductive elements, termed "cross-over conductors", is that the region of cross-over can be used to form an circuit element, such as a resistor or a capacitor. The properties of the material sandwiched between the conductive elements may be dependent upon the dielectric properties of the droplets which have impacted and cured on the upper surface of the bottom-most conducting element.

Preferably, a plurality of droplets comprise at least one droplet of one material and at least one droplet of another material.

Printing materials may include, but are not restricted to:

- conductive and semi-conductive polymers, for example:

co-polyaniline;

polyacetylene derivative;

poly(para-phenylene);

polythiophene;

inorganic polymers; and

particulates including, for example, gold, nickel coated polystyrene and graphite;

- polymer blends and mixtures;
- organically modified ceramics ("ormocers");
- organically modified silicates ("ormosils");
- sol-gels; and
- cermets.

Thus, the present invention can use low or zero toxicology-rated fluids.

The viscosity range is preferably less than or equal to 100 centipoise (cps), based on 100% solid and dilute systems. The surface energy of such fluids may be in the range from 15 to 75 dynes.cm^{-1}. Consequently, a low surface energy nozzle or a controlled wetting nozzle annulus may be required to minimise surface wetting and the concomitant drive voltage required to expel a droplet from the nozzle.

In yet another aspect, the present invention provides a circuit element formed from chemically-modified polymeric-based or inorganic-based fluid.

Preferably, the fluid comprises conductive particles. Preferably, the conductive particles have a dimension less than or equal to 1 micron.

In yet another aspect, the present invention provides a method of imparting electrical conduction to at least part of a partially cured insulating layer using electrostatically focused electrically conductive particles.

The conductive particles may be charged to assist directional steering of the particles towards a selected region of said layer. This method can be applied to the formation of an entire electrically conducting element, such as a track, or to a specific location, such as a contact region where the conductive particles improve local conduction to provide a region having a lower contact resistance and which may be used as a bonding platform. The rate of diffusion of the particles into the layer may be determined by at least one of the type and intensity of the radiation used to fix or fully cure the layer.

The size of an circuit element may be determined by at least one of surface wetting, droplet volume, and solid content of the fluid to be ejected, as well as any shrinkage that may take place for different degrees of curing.

The substrate surface energy dictates the control over the fluid spreading, or wetting, assuming that the curing process is implemented after the fluid has wet the surface. Controlled coalescence of sequential, in-line drops can be achieved either by modifying the software-controlled index distance that the printhead travels between successive droplet release, or alternatively, or additionally, irradiating the surface with a suitable secondary energy source which influences the fluid wetting and surface transport by increasing the rate of drying so as to promote thixotropy and a significant change in rheology. This control permits the build-up of material independently in all three dimensions.

The method may further comprise the step of electrically isolating the surface before forming said circuit element thereon. This step may comprise depositing an adhesion-promoting layer on said surface.

The surface may be flexible. For example, the surface may comprise a flexible plastic, preferably polyethylene, sheet. The surface may be either planar or irregular.

The circuit elements can form an enabling step for the generic technology of printing circuits on to temperature-sensitive substrates, such as polyethylene flexible plastic sheet. Such circuits include, but are not limited to, filters, resonators, networks, transmission lines, digital circuits, modulators and signal conditioners.

Advantageously the method further comprises the step of subjecting the deposition material to radiation treatment before, during or after deposition. The print surface may be subjected to radiation to prepare it for the deposition material. Employing in-situ UV and infrared radiation exposure can provide considerable scope for modifying the reaction of the droplet in order to achieve the required feature and profile.

The present invention will now be described by way of illustration only and with reference to the accompanying Figures in which:

Figure 1 shows three deposition heads directed towards a coincident drop site on a print surface;

Figure 2 shows an array of deposition heads;

Figure 3 shows a cross-sectional view of a deposition head in combination with a UV light source;

Figure 4 shows a cross-sectional view of a resistor;

Figure 5 shows a selection of profiles for a resistor;

Figure 6 shows a cross-sectional view of a capacitor;

Figure 7a shows a schematic diagram of an inductor; and

Figure 7b shows a cross-section along line A-A in Figure 7a.

Referring to Figure 1 a three-dimensional circuit element is formed on a printing surface using a drop-on-demand deposition technique to drop multiple droplets 20 of a deposition material from a number of deposition heads 22A, 22B, 22C. The deposition heads have a height above the printing surface between 5μm and 1000μm. Each deposition head 22A, 22B, 22C holds the deposition material and ejects it a droplet at a time on demand onto the print surface. The deposition materials comprise in excess of 0.01% solid matter and may be any one of the materials discussed in the introduction.

Each deposition head comprises a pressure generation cavity 26 with a profiled cylindrical nozzle 28 in one wall of the cavity and a PZT bimorph actuator 30 in an opposite wall. Each nozzle 28 defines a line of ejection which is representative of the path a droplet of deposition material will take upon ejection.

Figure 1 shows three deposition heads directed towards a single drop site, although any suitable number of deposition heads may be used to form the desired circuit element. Of course, each deposition head may be directed towards respective drop sites rather like a conventional printer head, as shown in Figure 2. Such a two-dimensional array 36 may provide for the simultaneous deposition of multiple droplets.

Figure 3 shows a deposition head 22 as part of a X-Y deposition system 50. The system 50 includes a quartz-halogen lamp 60 supplying UV light through an optical fibre 62 to the printing surface 64 onto which the droplets 66 are deposited. This system 50 subjects the deposition material to radiation treatment after it has been deposited for the purposes of curing the material or other processing.

The system 50 employs digital deposition servo drive motors for x-axis and y-

axis transport motion. A replaceable polymer deposition head 22, along with its associated polymer reservoir cartridge(s) 68, resides on the axis drive carriage plate. Integrated into the carriage plate is a set of annular fibres that permit close proximity UV and infrared radiation for surface pre-treatment, in-flight treatment and/or post deposition treatment. The annular radiation emitters are fed from a fibre optic 62 that is coupled at the opposite end to the light source 60. The deposition surface 64 may be electrostatically secured to the deposition frame. The use of a cooling fan 70 and cooling air directional ducting 72 maintains the system 50 at a working temperature.

The characteristics of the element to be produced are drawn on a computer screen using a suitable draw facility software package or are imported into the plotter drive computer memory using a digital scanning facility (with on board character recognition capability, as required). The finished map is digitised and the appropriate x-y co-ordinates are fed to the system interface so that the required element is formed at the location requested. The drive waveform to the droplet dispense pressure generator (polymer dispense head) is synchronised to the x-y placement co-ordinates, so that the required element is accurately placed. For specific surfaces it is possible to employ an adhesion enhancing liquid pre-treatment prior to depositing the required polymeric pattern.

Integral continuous or pulsed UV (also in conjunction with infrared radiation - thermally assisted curing) light source with illumination of the dispensing droplet via a fibre-optically fed focusing annulus may be located in close proximity to the dispensing head (or nozzle array). Note that in the limit (high value or high polymer dispense volume applications) this light source could be an excimer laser that employs a rotating mirror arrangement to create a fine line UV light beam that is continuously rotating around a selectable circular radius or more complex elliptical shape. The annulus can be formed by using a suitable retaining mould in the Y-spider plate, and with the use of a pre-shaped top casting cap, PMMA or alternative polymer can be injected into the

unit for a UV transmitting annulus with a particular optical focusing. It is envisaged that a suitable light source can be manufactured that would enable the annulus to be fed from a source that is also integrated onto the y-axis carriage plate.

The shape and surface of the nozzle 28 determines the energy needed to eject the droplet from the nozzle. A polished nozzle 28 will have a lower surface energy than an unpolished nozzle and therefore will more easily release a droplet. A low surface energy nozzle exit can be achieved using a variety of liquid coatings (i.e Montedison Galydene), however a more practical route is to gravure print a silicone loaded acrylic UV curing film on to the front of the nozzle plate (this exhibits a surface energy of less than or equal to 19 dyn cm (190μjoules)). One advantage of using such coating materials is that the nozzle can be made of both copper (wetting) and laminate material (wetting or non-wetting) giving more flexible control over the direction of droplet ejection. Both materials can be obtained in a variety of metal and laminate core thicknesses.

The nozzle may incorporate an integral piezoelectric bimorph nozzle shutter (not shown) to act as a sealant for the deposition material retained in the nozzle. This feature prevents ultraviolet light and water vapour from entering the nozzle when not in use. The shutter may comprise a plunger retained in the deposition chamber of the deposition head. Such a plunger means has a relative coaxial sliding fit with the nozzle whereby a plunger head aligns with the nozzle aperture to close the nozzle and in an open position the plunger is retracted into the chamber. By controlling the position of the plunger head with respect to the nozzle aperture, the deposition chamber size can be controlled thereby allowing an adjustable droplet of deposition material to be ejected.

The nozzle may comprise means for directly varying the size of the nozzle aperture whereby the means is an iris type arrangement.

A deposition control electric field generator may be used to generate an electric field in the vicinity of the nozzle to control the shape of a meniscus of the electrically responsive deposit materials. This is used to exert a pulling force on the droplets so that less energy is required by the actuators to eject the droplets from the nozzle chamber.

Material may be dispensed in a vacuum to facilitate the deposition of droplets of diameter substantially less than or equal to 1μm. If this were attempted in air then the drag induced by air resistance would distort the droplet and impair its dimensional stability and placement accuracy.

Examples of circuit elements formed using the technique of droplet ejection will now be described with reference to Figures 4 to 7.

Figure 4 is a cross-section of a polymeric resistor 200 formed on surface 202. The resistor 200 comprises an adhesion promoting layer 204 and controlled-resistance polymer 206 formed on the layer 204. The resistor 200 is connected to a conductive track 208 formed on the surface 202 by a polymeric electrical contact 210. An isolating layer 212 is formed over the entrire surface of the resistor and the conductive track.

Variation in the height *d*, width *w* and length *L* of the resistor 200, that is, the volume of the resistor 200, controls the specific resistance value *R* of the resistor 200 according to the equation:

$$R = \frac{\rho \cdot L}{w \cdot d}$$

where rho is the resistivity of the resistance polymer 206. Of course, the solid content per droplet will influence the resistivity of the polymer 206.

The resistor 200 may take any three-dimensional shape as determined by the designer of the resistor in view of the intended purpose of the resistor. Figure 5 shows top views of resistors 200A to 200D, and side views of resistors 200E to 200H. In addition, both of these profiles may be changed by sectioning the resistor following formation.

Electron and hole barrier reducing layers/interface doping can be used to enhance the functionality and stability of the resistor.

Figure 6 is a cross-section of a polymeric capacitor 300 formed on surface 302. The capacitor 300 comprises a first polymeric conductive layer 304, a polymeric dielectric layer 306 and a second polymeric conductive layer 308. The first conductive layer 304 may be deposited on an adhesion promoting layer 310; however, depending on the nature of the surface 302, this adhesion promoting layer may not always be necessary. As shown in Figure 6, the edges 312 of the dielectric layer 306 are locally thickened in order to eliminate the electric field breakdown due to current bunching at the edges of the conductive layers. An isolating layer 314 is formed over the entire surface of the capacitor 300.

Similar to the resistor, the capacitor can take any shape as determined by the designer of the capacitor in view of the intended purpose of the capacitor. For example, the dielectric layer 306 may comprise a plurality of layers of different material aligned either substantially parallel to or substantially perpendicular to the conductive layers 304 and 308.

Figures 7a and 7b shows schematic diagrams of an inductor 500 formed using a droplet deposition technique. The inductor 500 comprises a first polymeric conductive layer 502 formed on surface 504. An insulator layer 506 is then deposited over the conductive layer 502 so as to expose contacts 508 and 510 of the conductive layer 502. A second polymeric conductive layer 512 is subsequently deposited in the form of a spiral having a centre coincident with

contact 510 and an end 514 substantially aligned with the contact 512. The size of the inductance of the inductor is determined by the number of "turns" of the spiral 512 and the material from which the insulator layer is formed.

It will be understood that the present invention has been described above purely by way of example, and modifications of detail can be made within the scope of the invention.

Each feature disclosed in the description, and (where appropriate) the claims and drawings may be provided independently or in any appropriate combination.

CLAIMS

1. A method of forming a circuit element on a surface using the technique of droplet ejection to deposit droplets of deposition material, said method comprising depositing a plurality of droplets on said surface to form said element so as to comprise multiple discrete portions, at least two adjoining portions being formed from different deposition materials.

2. A method according to Claim 1, wherein the circuit element comprises an electrically conductive element.

3. A method according to Claim 1 or 2, wherein the circuit element comprises a plurality of stacked electrically conductive elements connected by via holes to provide electrical conduction between layers.

4. A method according to Claim 3, wherein the circuit element further comprises at least one isolation layer, the or each isolation layer being disposed between adjacent elements.

5. A method of forming a circuit element comprising stacked electrically conductive elements on a surface using the technique of droplet ejection to deposit droplets of deposition material, said method comprising depositing a plurality of droplets to form a first conductive element, depositing a plurality of droplets to form an isolation layer on said first conductive element and depositing a plurality of droplets on said isolation layer to form a second conductive element.

6. A method according to Claim 4 or 5, wherein the droplets forming the conductive elements and the droplets forming the isolation layer are supplied by respective droplet deposition printheads.

7. A method according to Claim 4 or 5 wherein the droplets forming the conductive elements and the droplets forming the or each isolation layer are supplied by a butted droplet deposition printhead having a plurality of separate fluid supplies.

8. A method according to any of Claims 2 to 7, wherein the or each electrically conductive element comprises a track on a printed circuit board.

9. A method according to any of Claims 2 to 8, wherein the conductivity of the or each electrically conducting element is in the range from 10^2 to $4x10^5 S.cm^{-1}$.

10. A method according to Claim 1, wherein the circuit element is an electrical resistor.

11. A method according to Claim 10, wherein the resistor is formed from polymeric material and includes a layer for promoting adhesion between the polymeric material and the surface, said method comprising the steps of depositing said layer on said surface and depositing said polymeric material on said layer to form said resistor.

12. A method according to Claim 11, wherein the droplets forming the polymeric material and the droplets forming the adhesion promoting layer are supplied by respective droplet deposition printheads.

13. A method according to Claim 11, wherein the droplets forming the polymeric material and the droplets forming the adhesion promoting layer are supplied by a butted droplet deposition printhead having a plurality of separate fluid supplies.

14. A method according to Claim 1, wherein the circuit element is an electrical capacitor.

15. A method according to Claim 14, wherein said capacitor comprises a first polymeric conductive layer formed on said surface, a polymeric dielectric layer formed on said first conductive layer and a second polymeric conductive layer formed on said dielectric layer, said method comprising the steps of depositing said first polymeric conductive layer on said surface, depositing said polymeric dielectric layer on said first conductive layer and depositing said second polymeric conductive layer on said dielectric layer.

16. A method according to Claim 15, wherein said capacitor further comprises a layer for promoting adhesion between said first conductive layer and said substrate, said method comprising depositing said layer on said substrate before deposition of said first conductive layer.

17. A method according to Claim 15 or 16, wherein opposing side edges of said dielectric layer are locally thickened to eliminate electric field breakdown due to current bunching at the edges of the conductive layers.

18. A method according to any of Claims 15 to 17, wherein the droplets forming respective layers are supplied by respective droplet deposition printheads.

19. A method according to any of Claims 15 to 17, wherein the droplets forming respective layers are supplied by a butted droplet deposition printhead having a plurality of separate fluid supplies.

20. A method according to Claim 1, wherein said circuit element is an electrical inductor.

21. A method acording to any of Claims 10 to 20, further comprising the step of depositing an isolating layer over the surface of said element.

22. A method of forming a plurality of circuit elements on a surface using

the technique of droplet ejection to deposit droplets of deposition material, said method comprising depositing a plurality of droplets to form a first circuit element, depositing a plurality of droplets to form an isolation layer on said first circuit element and depositing a plurality of droplets on said isolation layer to form a second circuit element.

23. A method according to Claim 22, wherein said circuit elements comprise elements as recited in any of Claims 2 to 4 and 10 to 20.

24. A method according to any preceding claim, wherein a plurality of droplets comprise at least one droplet of one material and at least one droplet of another material.

25. A method according to any preceding claim, wherein the droplet viscosity range is less than or equal to 100 centipoise.

26. A method according to any preceding claim, wherein the surface is flexible.

27. A method according to Claim 26, wherein the surface comprises a plastic sheet.

28. A method according to any preceding claim, further comprising the step of subjecting the deposition material to radiation treatment before, during or after deposition.

29. A method according to any preceding claim, wherein the surface is subjected to radiation to prepare it for the deposition material.

30. A circuit element formed on a surface using the technique of droplet ejection to deposit droplets of deposition material, said element comprising multiple discrete portions, at least two adjoining portions being formed from

different deposition materials.

31. A circuit element formed from chemically-modified polymeric-based or inorganic-based fluid.

32. An element according to Claim 31, wherein the fluid comprises conductive particles.

33. An element according to Claim 32, wherein the conductive particles have a dimension less than or equal to 1 micron.

34. A method of imparting electrical conduction to at least part of a partially cured insulating layer using electrostatically focused electrically conductive particles.

35. A method according to Claim 34, wherein the conductive particles are charged to assist directional steering of the particles towards a selected region of said layer.

36. A method according to Claim 34 or 35, wherein the rate of diffusion of the particles into the layer is determined by at least one of the type and intensity of the radiation used to fix or fully cure the layer.